Properties and Manifestations of Neutrinos

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Based on a review work with Strumia, titled *"Neutrino Masses and Mixings and ..."*, that we leave on the web for some yr to purge and update on:
`http://astrumia.web.cern.ch/astrumia/review.html`
(please help us with feedback, comments, corrections, criticisms).

Also included, works with Cirelli, Marandella (phenom.); with Bajc, Melfo, Senjanović (theory); with Costantini, Ianni, Pagliaroli (ν astr.).

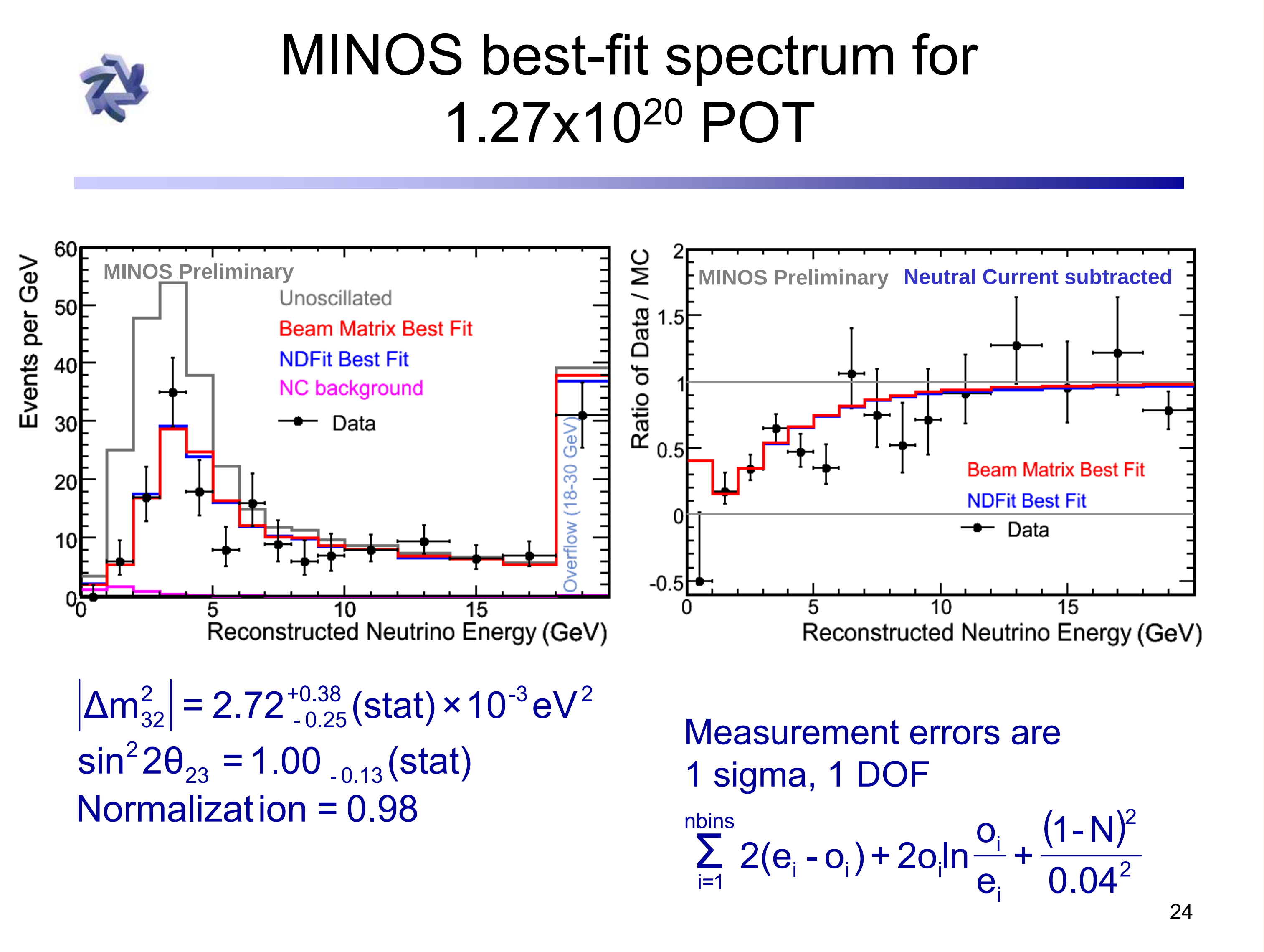
I will show only selected results and furthermore emphasize theoretical aspects: shame on me (I know it is not an excuse, but I had no choice).

1 Oscillations, neutrino masses, and all that

The only firm-evidences/strong-hints of neutrino masses come from oscillations. The potential of this method was immediately understood by Pontecorvo and it is today clear to everybody.

Other approaches, such as the search of imprints on the β-decay spectrum are at the moment producing upper bounds. Perhaps the exception is $0\nu2\beta$, a process possible for massive Majorana neutrinos.

It is probably fair to say that a reference minimal picture with 3 massive ν *accounts for the main experimental facts. This is directly challenged by the anomalies of LSND,* $0\nu2\beta$*, NuTeV and less indirectly by other facts.*



MINOS best-fit spectrum for $1.27\text{x}10^{20}$ POT

$$\left|\Delta m^2_{32}\right| = 2.72^{+0.38}_{-0.25}\,(\text{stat}) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\,(\text{stat})$$

Normalization = 0.98

Measurement errors are 1 sigma, 1 DOF

$$\sum_{i=1}^{\text{nbins}} 2(e_i - o_i) + 2o_i \ln\frac{o_i}{e_i} + \frac{(1-N)^2}{0.04^2}$$

1.1 Oscillations are simple !

1) KamLAND (react.), Gallex/GNO & SAGE (solar ν, low E_ν):

$P_{\nu_e\nu_e} = 1 - \sin^2 2\theta_{12} \cdot \sin^2(\Delta m^2_{12}\ L/4E)$, $\theta_{23} = 36^\circ - 54^\circ$

2) SK (atm. ν), K2K & MINOS (accel.):

$P_{\nu_\mu\nu_\mu} = 1 - \sin^2 2\theta_{23} \cdot \sin^2(\Delta m^2_{13}\ L/4E)$, $\theta_{12} \sim 30^\circ - 38^\circ$

3) CHOOZ (react.):

$P_{\bar\nu_e\bar\nu_e} = 1 - \sin^2 2\theta_{13} \cdot \sin^2(\Delta m^2_{13}\ L/4E)$, $\theta_{13} < 10^\circ$

4) LSND, Karmen (π at rest):

$P_{\bar\nu_\mu\bar\nu_e} = \sin^2 2\theta_{14} \cdot \sin^2(\Delta m^2_{14}\ L/4E)$, $\theta_{14} \sim 1^\circ$

Note the limit for the phase going to infinity, the maximal angle $\theta_{max} = 45^\circ$, and the symmetries of $\sin 2\theta$

The first 3 indications fit in 3 flavor framework;
the last (4 σ) is being tested by MiniBOONE.

[in matter, oscillations are a bit less simple]

The phase shift of ν_e from $\nu_e e \longrightarrow \nu_e e$ contributes an additional term to the Hamiltonian of propagation in matter: $\delta H_\nu = \mathrm{diag}(1,0,0) \times \sqrt{2}\, G_F\ \rho_e(x)$

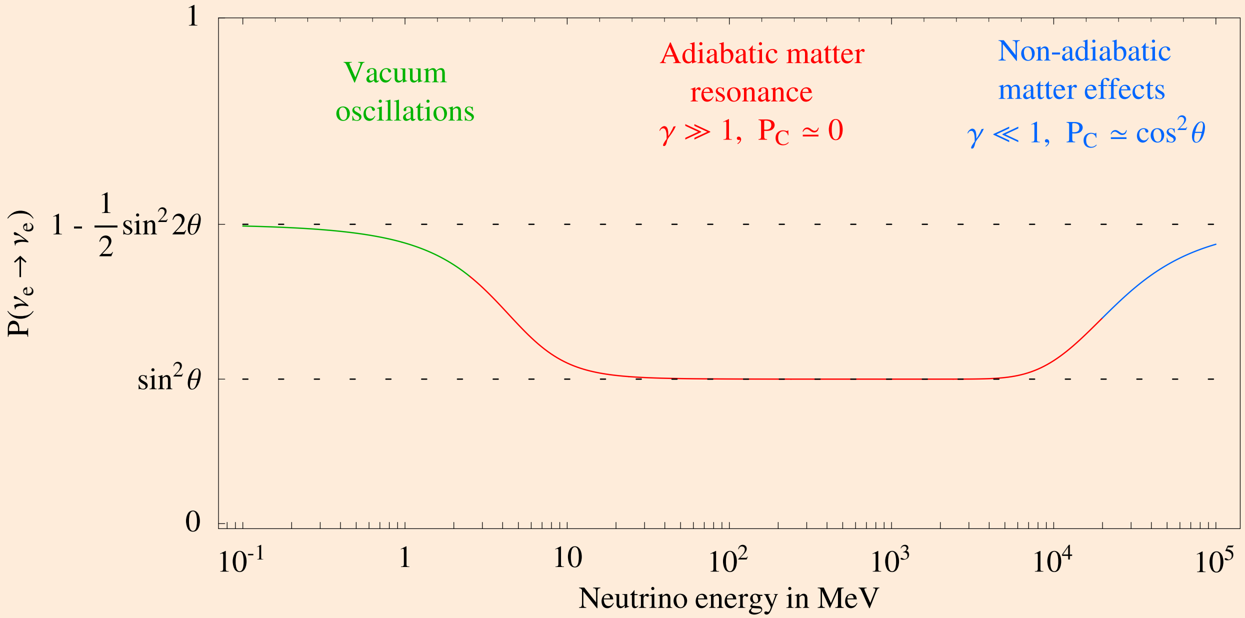


Figure 1: *Solar ν_e of relatively high energy are produced as the Hamiltonian eigenstates $\nu_2(\rho_e)$ in the center of the sun, and remain mass eigenstates till the exit. Thus, $\langle \nu_e | \nu_2 \rangle = \sin\theta_{12}$ as demonstrated by SNO.*

[status of the three flavor picture]

Oscillations entail 6 param's: 2 mass differences, 3 mixing angles 1 phase, that permit to account for the main 2 experimental 'anomalies'.

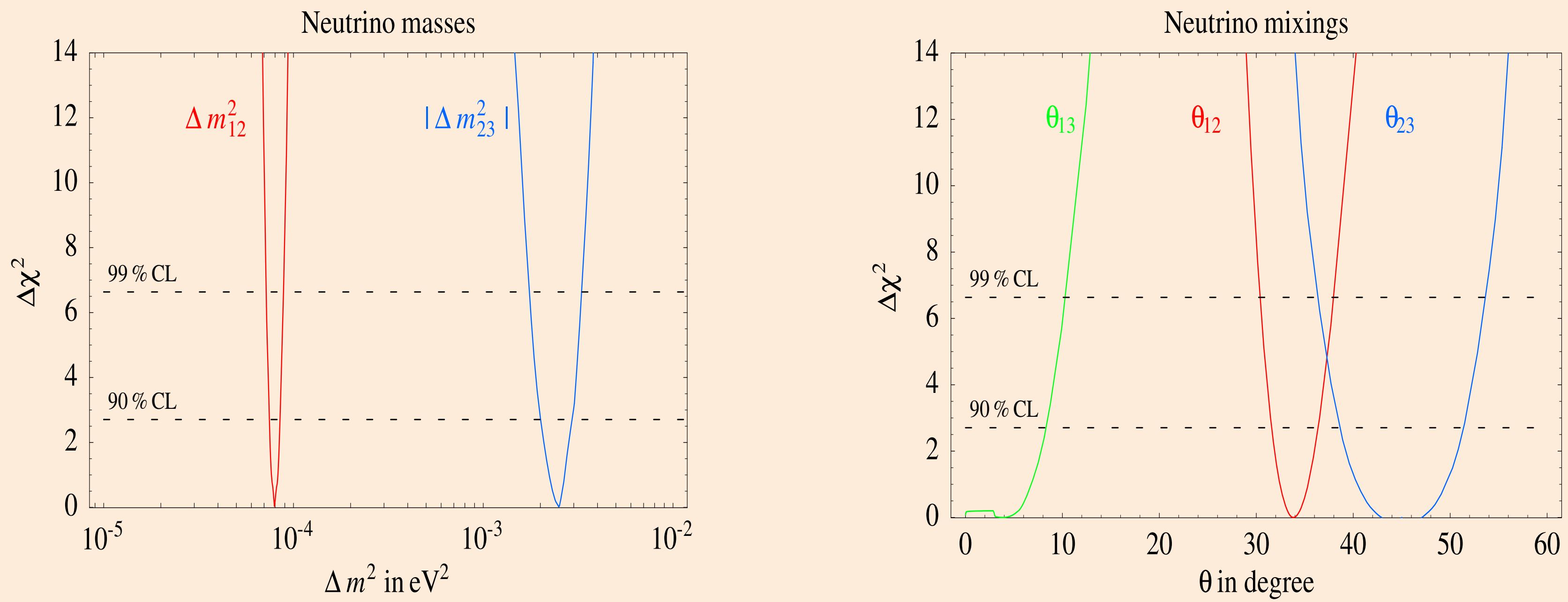


Figure 2: *Summary of what we know on the parameters of oscillations, the CP phase being simply unknown;* Δm^2_{23} *will improve with MINOS.*

1.2 Observables connected to ν-mass (still simple)

$M = U^* m U^\dagger$	Majorana masses
$H_\nu = U({}^{m^2}/_{2E})U^\dagger + \sqrt{2}G_F \mathrm{diag}[\rho_e, 0, 0]$	Oscillations
$m_\beta^2 = \sum_i \lvert U_{ei}^2 \rvert \times m_i^2$	β-decay
$M_{ee} = \sum_i U_{ei}^2 \times m_i$	$0\nu2\beta$-decay
$m_{\rm cosm} = \sum_i m_i$	cosmology

- *These expressions are strictly correct in the 3 flavor picture (e.g., with a “large” ν mass, kinks in the β spectrum may appear).*
- *Then, Majorana means 9 observable parameters.*
- *If the mass is Dirac, 7 param.s & $0\nu2\beta$ absent; the rest is unchanged.*
- *More observables possible, but none reaches a useful sensitivity.*

[e.g., $0\nu 2\beta$ - neutrinoless double beta decay]

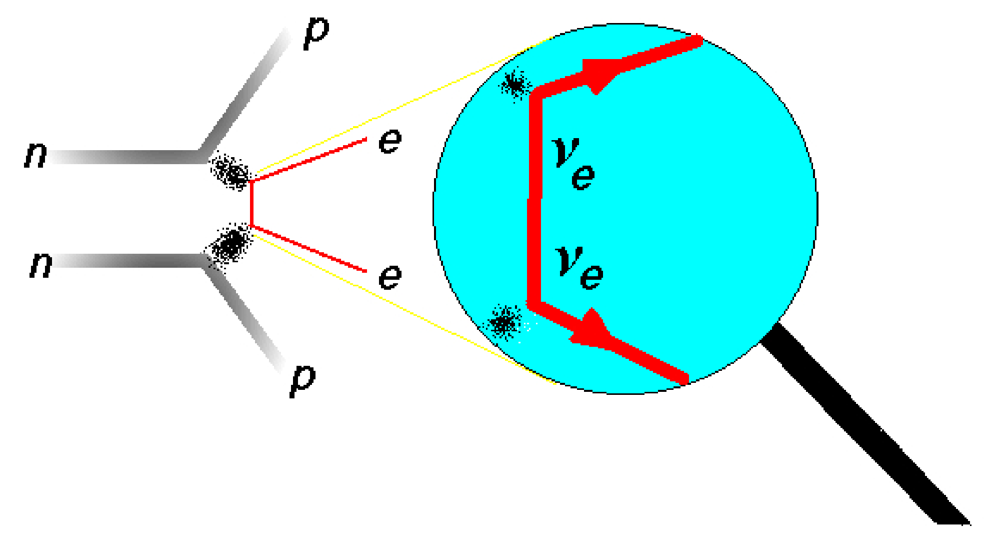


Figure 3: $(A, Z) \to (A, Z+2) + 2e^-$ *arises with* $\Delta L_e = 2$, *e.g., Majorana neutrino masses, with structure* $\nu_L^t C M \nu_L$. *If the* β*-decay is forbidden,* $0\nu 2\beta$ *could be searched seen as a peak in the endpoint of* $2\nu 2\beta$.

Maybe it is seen already? And what we deduce from oscillations?

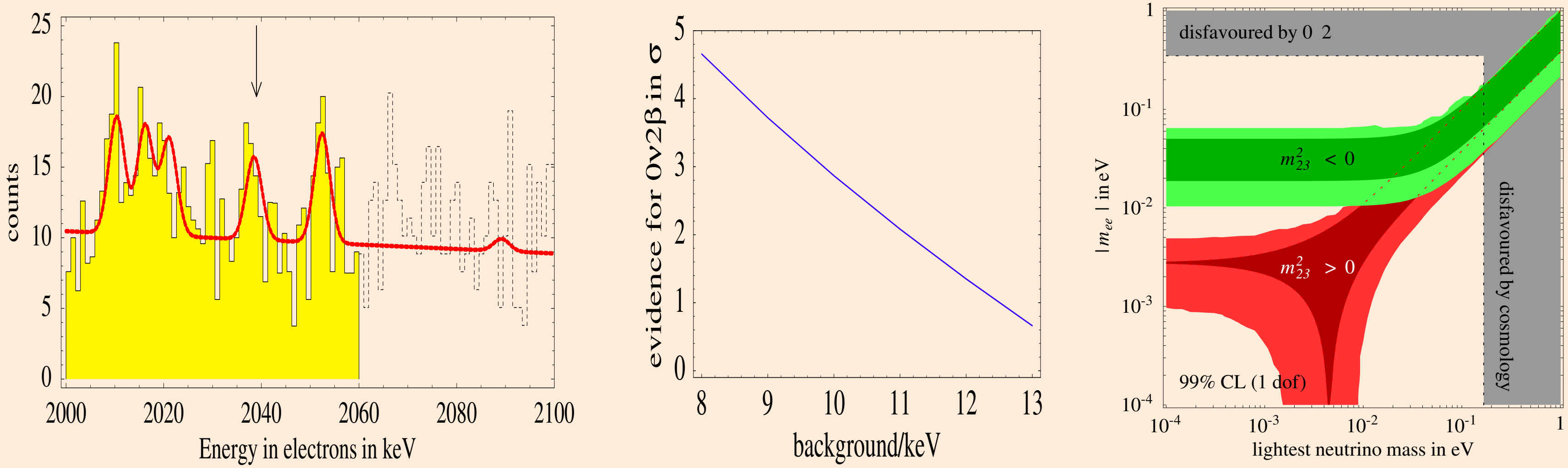


Figure 4: *a) Final Heidelberg-Moscow spectrum (yellow) and possible peaks (red) resulting from a fit. b) Confidence level of the* $0\nu2\beta$ *peak as a function of the background level. c) Expectations for* $0\nu2\beta$ *on the basis of oscillations; the lightest* ν *mass is a free parameter.*

2 Theoretical particle physics aspects

Some people think that a Dirac neutrino mass $\bar{\nu}_L \nu_R$ is more economical (or attractive) than Majorana's.

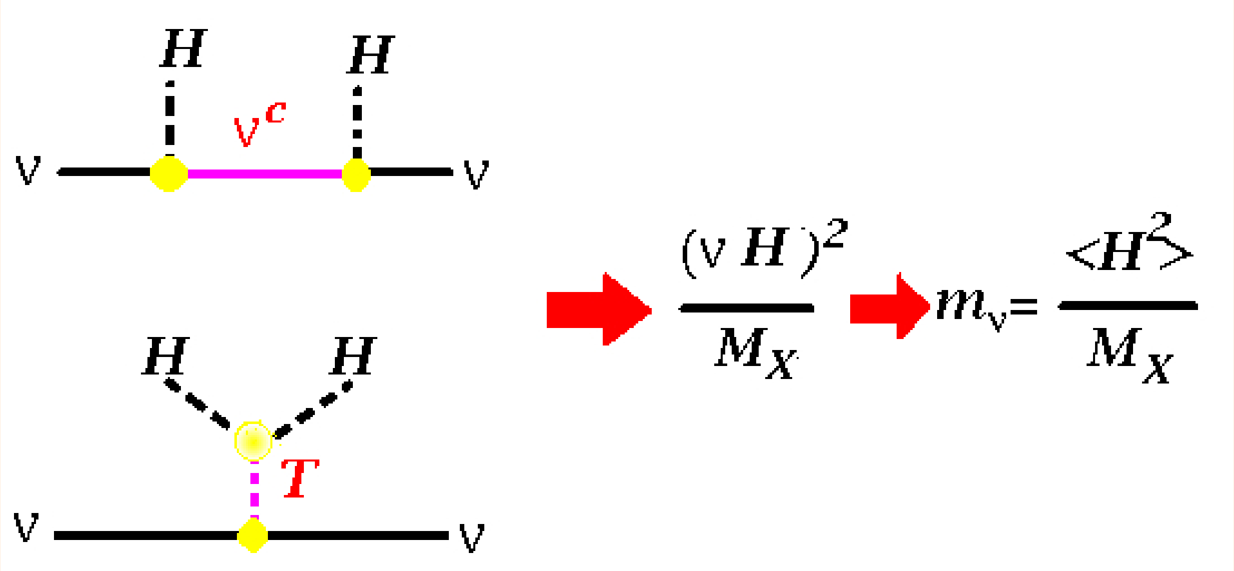
However, this requires adding a ν_R*, a particle without EW (gauge) interactions; thus, a Majorana mass* $\nu_R^t C M \nu_R$ *is always possible.*
This mass scale has nothing to do with the EW scale (say, with m_W*).*

Also: adding ν_R makes the $\underline{\text{spectrum}}$ fully left-right symmetric, and this suggests strongly that SU(2)$_R$ has a dynamical meaning.

Thus I like better (and hereon consider) only Majorana masses.

2.1 Seesaw as an answer and as a question

Light ν masses could witness the existence of new physics scale:



Is this situation ☺, or it is ☹ ? Probably, it is simply 😐.

More discussion follows.

2.2 Do we descend from ν's?

The SM is *quantitatively* unable to produce the baryon asymmetry in the course of the big-bang (the program of Sakharov). But since we should modify SM anyways, what about the model with massive ν?

The decay of $N = \nu_R + \nu_R^c$ *can produce a lepton asymmetry, that SM non-perturbative effect translate into a baryon asymmetry (Fukugita & Yanagida); this is very promising, despite model dependences.*

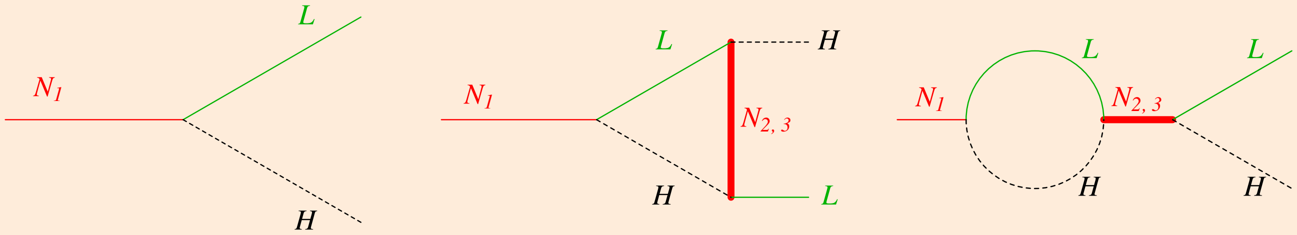
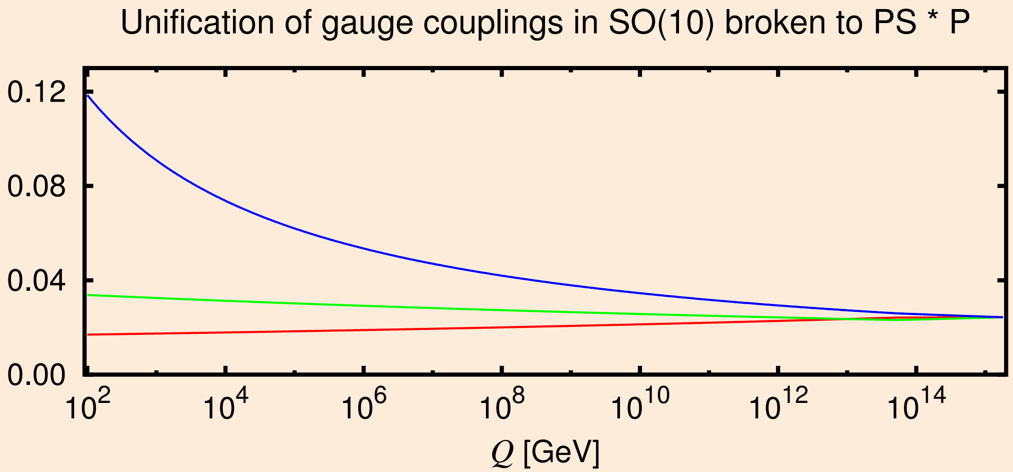


Figure 5: *The interference term leads to CP violation*

2.3 The power of GUT

Consider a (non-supers.) SO(10) model where gauge unif. happens via

$$\text{SO(10)} \xrightarrow{54_H} \text{Pati-Salam}\times\text{Parity} \xrightarrow{126_H} \text{SM}$$



ν masses get tied to gauge scales, $M_{interm.} \approx 5 \times 10^{13}$ GeV.

(this model has a relatively fast $p \longrightarrow \pi^0 e^+$, but quantitative statements require studying closely fermion masses and the heavy spectrum)

3 Neutrino astronomy & astrophysics

There is a wide interest in the detection of neutrinos from cosmic sources. This is largely an open field.

Oscillations and other particle physics effects (on ν and/or on the sources) can modify the observable quantities in many ways.

Yet there are large uncertainties on the expectations, so that the primary aim seems to be ν astronomy & astrophysics.

That's why the title and why I focus on these aspects in the last 4 pages.

3.1 Core collapse supernovæ

Super-K, LVD, KamLAND, SNO, Baksan, ... [10 MeV range]

Most of the gravitational energy from the formation of a neutron star (black hole) ~ 10 % $M_\odot \times c^2$, goes in thermalized ν radiation emitted in ~ 10 sec.

> *A definitive theory of the explosion and of ν emission is lacking; could mean new physics, but (surely) the problem is difficult.*

SN1987A GAVE US THE ONLY ν SIGNAL WE HAVE.

Observations seems to consistent with expectations, despite several puzzles in the interpretation: average energy KII $=$ IMB$/2$; excess of directionality; large number of Baksan events; Mont Blanc events.

[on the 12 events in Kamiokande-II]

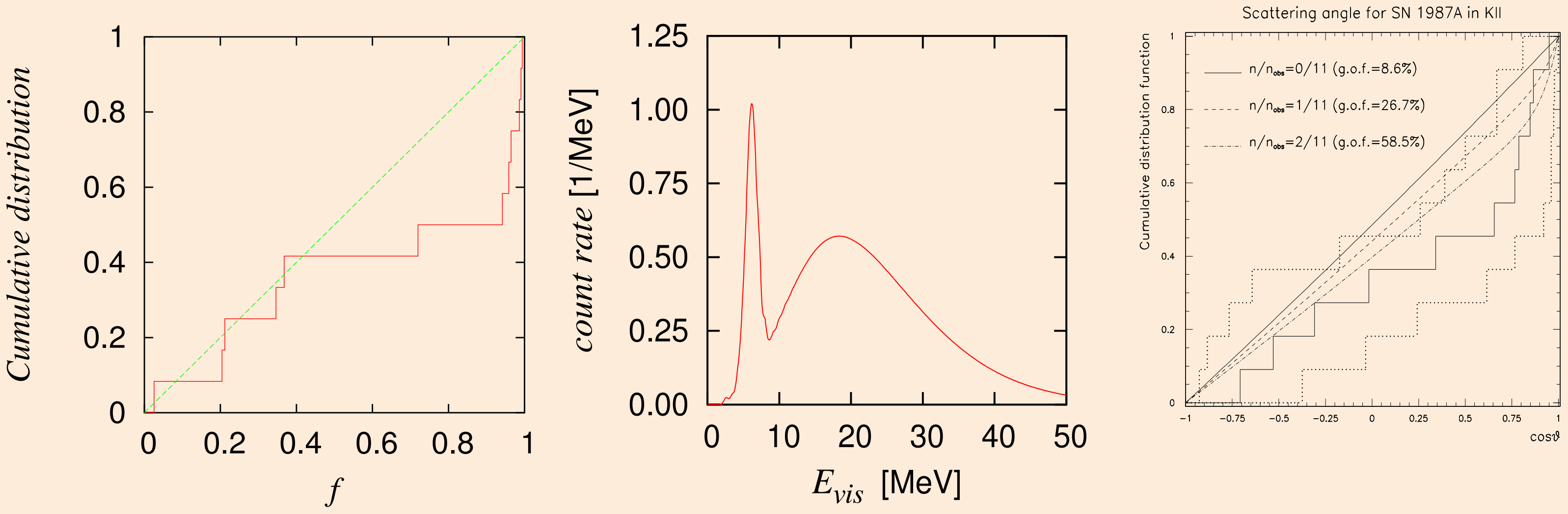


Figure 6: *Distributions on the volume (cumulative); on the energy (differential, theoretical); on the angle (cumulative). Suggest the presence of background events on the surface of the detector and at low energy, and possibly a few elastic scattering events.*

3.2 Supernova remnants

KM3NeT, IceCUBE [TeV-PeV range]

Strongly suspected to be the accelerators of CR in our Galaxy:
Baade & Zwicky 34, Fermi 49-54, Ginzburg* & Syrovatsky 64

New VHE γ-rays observations (H.E.S.S., Magic) suggest $pp \to \pi^0\ X$.

> *Neutrinos are also produced* $pp \to \pi^\pm\ X$ *and in principle can give a smoking gun in large neutrino telescopes*

A POSSIBLE PROBLEM: THE LOW COUNTING RATES.

A nearby SNR, Vela Jr (still to be studied in details) could be the best hope for ν telescopes in the Mediterranean.

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* *Tomorrow will be his* 90^{th} *birthday...*

[easy to deduce ν from H.E.S.S. data !]

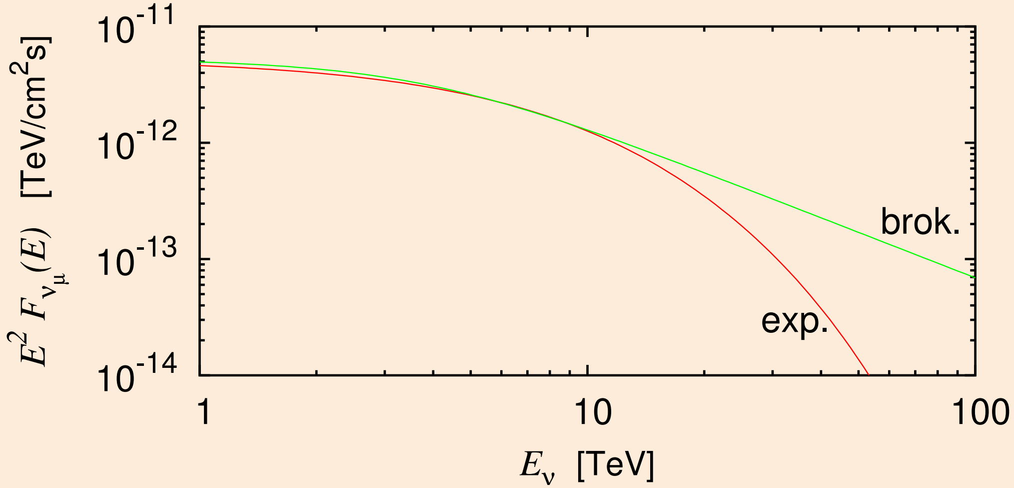

Figure 7: *Calculated VHE ν spectrum obtained from VHE γ-rays. Means $\sim 5\ \mu^{\pm}$ per km^2 per year in an ideal detector located in the Mediterranean. The effect of the cut (median neutrino energy 3 TeV) makes it more difficult to disentangle the atmospheric neutrino events–the background.*

4 Discussion

The field of ν is lively and interesting. Many remarkable experimental progresses. Reasonable to expect more interesting things soon. *(Are oscillations discovered? I propose a poll on that).*

Theoretical particle physics of ν is in a difficult position. Several open questions regard ultrahigh energy scales. Yet, I feel that several ideas deserve to be explored/updated (GUT, leptogenesis, etc.) Also, theory offers connections with other fields & observables.

Finally, I wish to recall that ν do not belong exclusively to particle physics! Interesting things are happening in other sectors of physics and there is a lot of work to be done (also for theorists, I hope).

Thanks for the attention!

5 Appendices

Just a few backup slides, in case you want to know more on:

- θ_{13}, the missing link in the 3 flavor picture;
- the interpretation of LSND anomaly, today;
- other hypothetical neutrino sources;
- a standard interpretation of SN1987A neutrinos;
- the quality of H.E.S.S. observations of SNR.

5.1 The missing mixing

In order to proceed with oscillations (e.g., with CP phase) the first step is to know the size of the mixing θ_{13}.

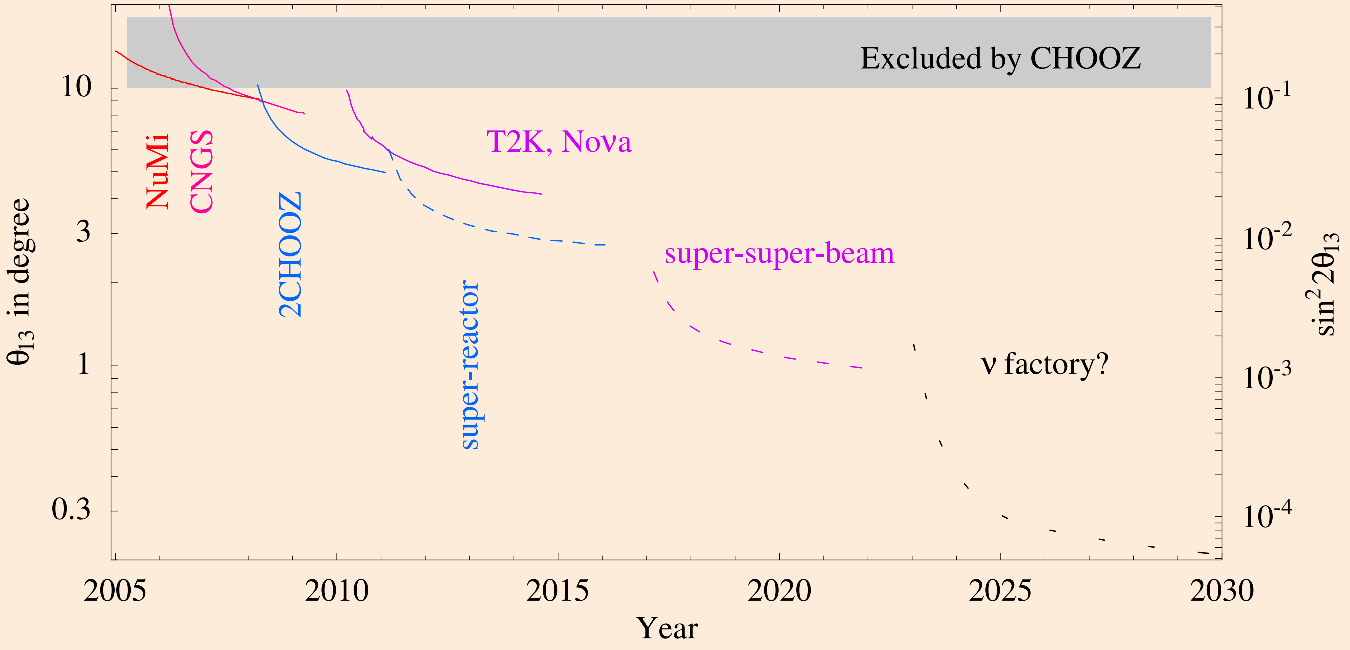

Figure 8: *Expected sensitivity of planned and future experiments.*

5.2 LSND before MiniBOONE

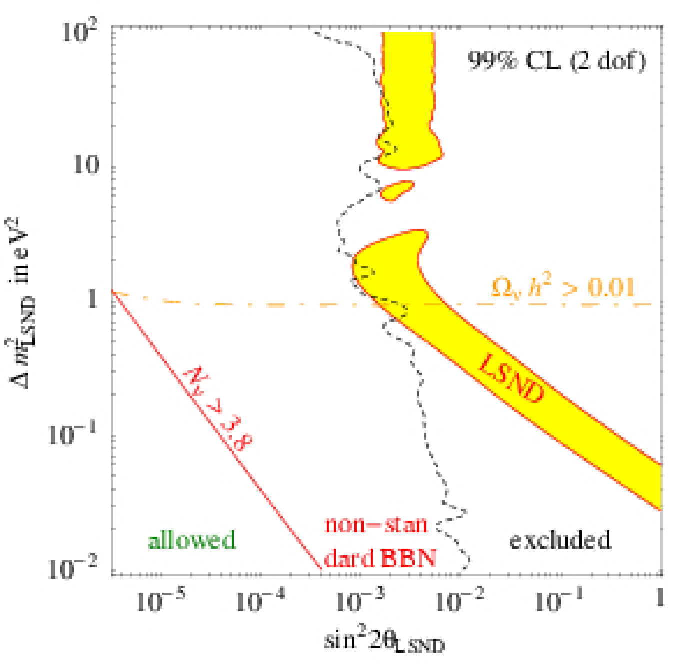

Figure 9: *Interpretation of LSND in the 3+1 scheme. the allowed region is compared with the excluded one (both at 99 %). Also shown: BBN region with* $N_\nu = 3.8$ *and cosmological region with* $\Omega_\nu h^2 = 0.01$.

5.3 Other neutrino sources

Auger, ANITA [EeV range]

Active Galactic Nuclei plausible sources of UHE CR (and thus of ν)

and/or possibly

Cosmogenic ν from collisions with CMB: Berezinsky & Zatsepin 69.

IceCUBE, KM3NeT, Mton WC [GeV-TeV range]

Annihilation of dark matter in Earth or Sun.

[e.g.: if we ever detect DM neutrinos...]

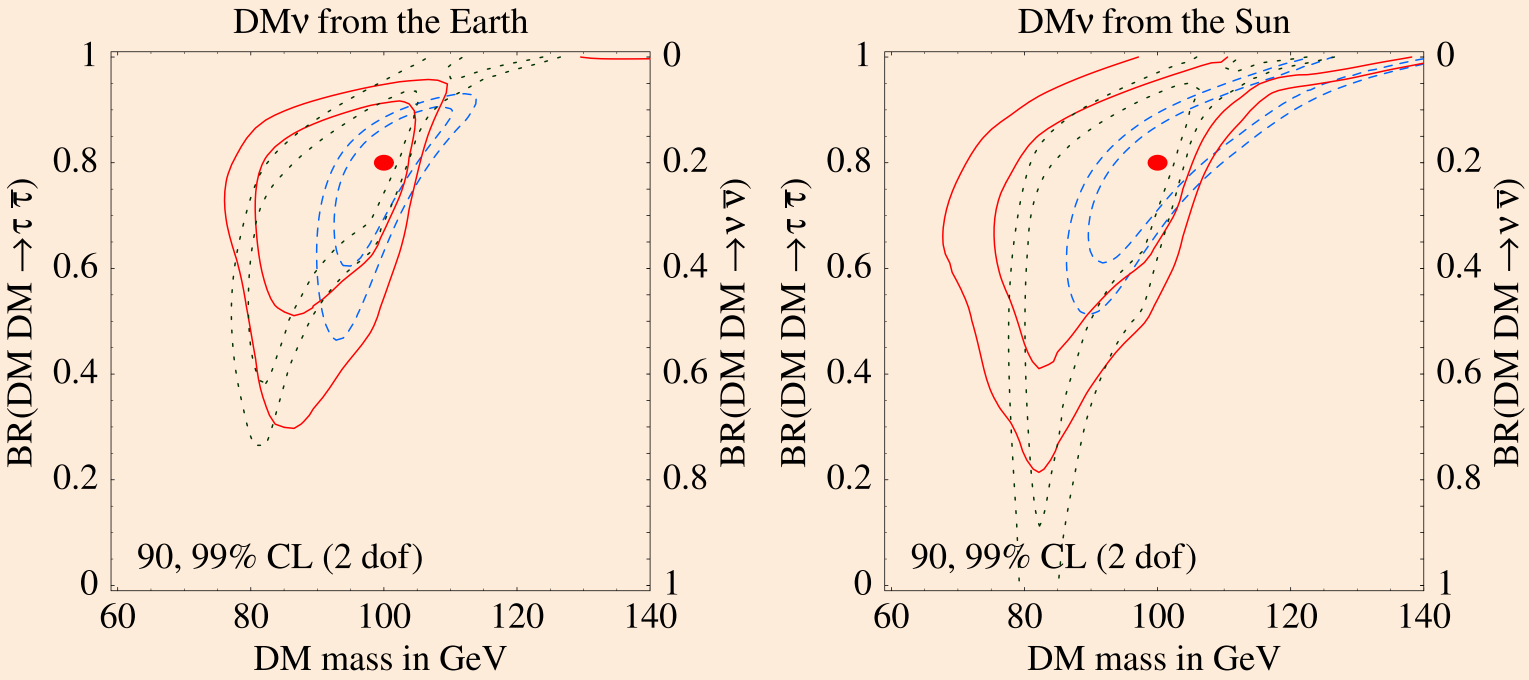

Figure 10: *Reconstruction of the DM properties from hypothetical samples of 1000 thoroughgoing μ, 100 contained μ, 200 showers.*

5.4 A standard interpretation of SN1987A

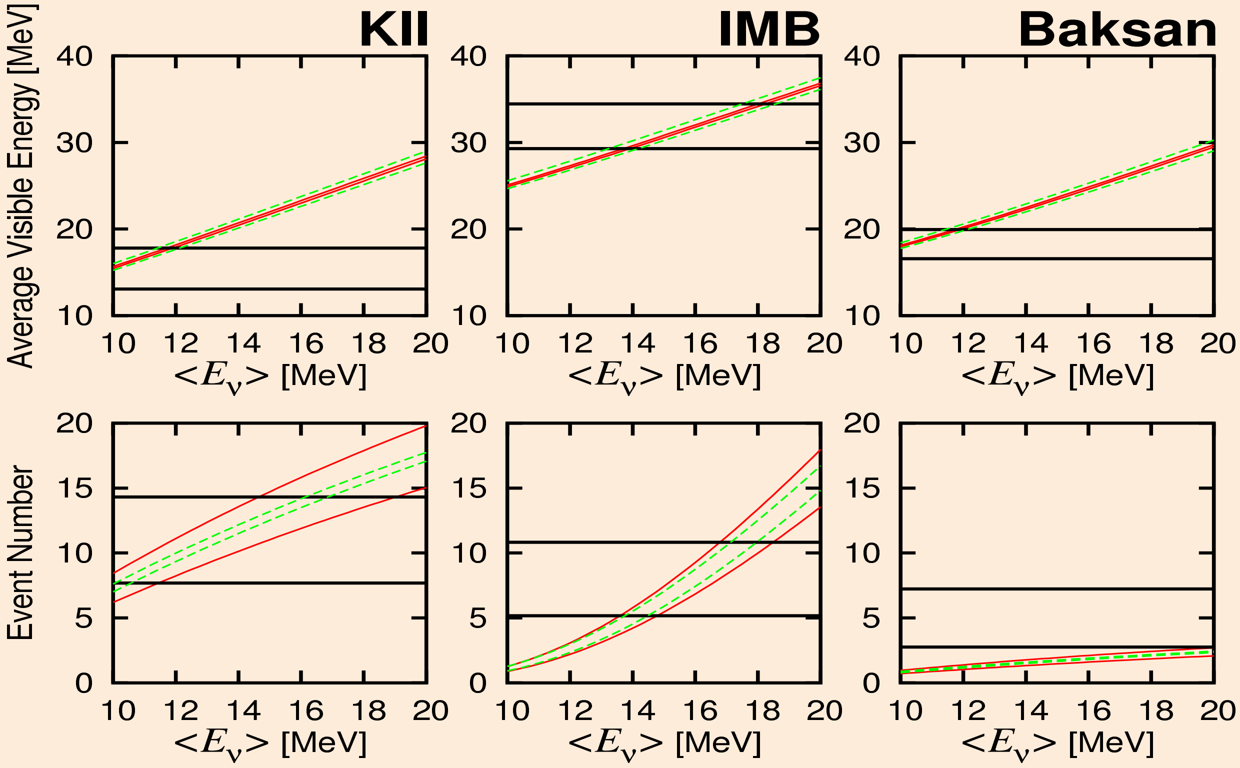

Figure 11: *Horizontal lines, experimental values; inclined lines, theoretical values, as a function of the average antineutrino energy. Assumes that all events are* $\bar{\nu}_e p \to n e^+$ *('inverse beta decay')*

5.5 RX J1713.7-3946 as seen by H.E.S.S.

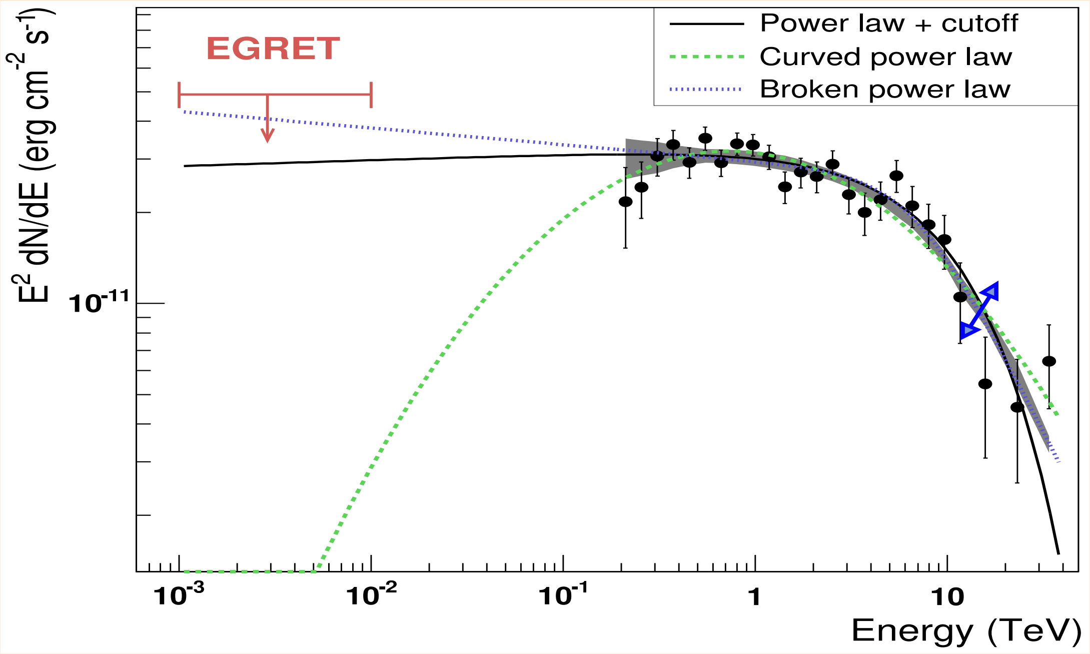

Figure 12: *Determination of VHE γ spectrum by the H.E.S.S. telescope along with phenomenological fits. Hadronic origin (i.e., from CR) suggested/favored, but essential to exclude a leptonic (i.e., from $e^{\pm}$) origin.*

6 Historical notes

A very good reference on historical ν matter till 1980 is the review of Pontecorvo on Uspekhi, *Pages in the development of neutrino physics.*
I like a lot the first 4 tables:
tab. I, *1896-1956,* from radioactivity till discovery of free ν;
tab. II, *1941-1967,* weak processes beyond β decay;
tab. III, *1959-1980,* high energy ν, 2 ν, EW interactions;
tab. IV, *1939-1980,* ν in astrophysics, astronomy and cosmology.

Several new facts since then, and I begin recalling the main ones regarding ν.

I also wish to list that a number of interesting points that have been made in theoretical particle physics.

[experiments / observation]

SOLAR ν: Gallex/GNO & SAGE 91-, SNO 01-, KamLAND 03-

ATMOSPHERIC ν: Super-Kamiokande 98- (Macro, Soudan etc)

$\bar{\nu}_e$ DETECTORS: CHOOZ 97. LSND 98.

LONGBASELINE: K2K 01, NuMi 06, CNGS 06-

SUPERNOVA ν: IMB, KamiokandeII, Baksan, Mont Blanc(?), 87

NON OSCILLATIONS: Mainz & Troitsk; Heidelberg-Moscow, IGEX, Cuoricino ...; cmb & lss observations.

ALSO: $N_\nu = 3$ from bbn & lep; bounds on μ_ν, lfv, p-decay...

[phenomenology / theory]

MATTER EFFECT: Wolfenstein 78, Mikheyev Smirnov 86

BARYOGENESIS / LEPTOGENESIS: Sakharov 67, ’t Hooft 76, Manton 83; Kuzmin Rubakov Shaposhnikov 85; Fukugita Yanagida 86.

ν IN GAUGE THEORIES, SEESAW: Minkowski 77; Yanagida 79, Gell-Mann Ramond Slansky 79, Mohapatra Senjanovic 79. Lazarides Shafi Wetterich 81, Mohapatra Senjanovic 81.

ν IN GAUGE THEORIES, GUT: Pati Salam 74; Georgi Glashow 74; Fritzsch Minkowski 75, Georgi 75. Senjanovic, 75-.

Contents